COMPONENT DESIGN, DEVELOPMENT, AND TESTING OF AN INDUCTIVE VOLTAGE ADDER (IVA) SYSTEM FOR JUPITER

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Abstract

Jupiter is a proposed 15-20 MJ laboratory x-ray source. It would store ~100 MJ in the Marx generators and deliver ~ 500 TW to drive high power z-pinch implosions.

The pulsed power requirements for Jupiter were evaluated by a national review panel[1] which concluded that the modular IVA technology as used in HERMES III[2] is capable of meeting these requirements. Modularity of construction permits design verification with less than a full size system and offers the flexibility to meet changing requirements. A program to validate this approach at the required power levels has begun with the construction and testing of components that will comprise a full scale IVA generator module.

The IVA module will provide a nominal 10 MV, 1.8 MA, 100 ns FWHM output pulse and will consist of four submodules. Each submodule is composed of a Marx generator, two Intermediate Energy Storage Capacitors (ISCs) four Pulse Forming Lines (PFLs), one Voltage Adder Cavity (VAC), plus other associated switches and hardware. A conceptual design for this IVA module has been completed.

Initial designs for the ISC, PFL, and their gas switches are also complete and hardware has been procured. Testing of these components is underway at Sandia National Laboratories. Discussions of these designs and results of tests are presented in this paper.

I. Introduction

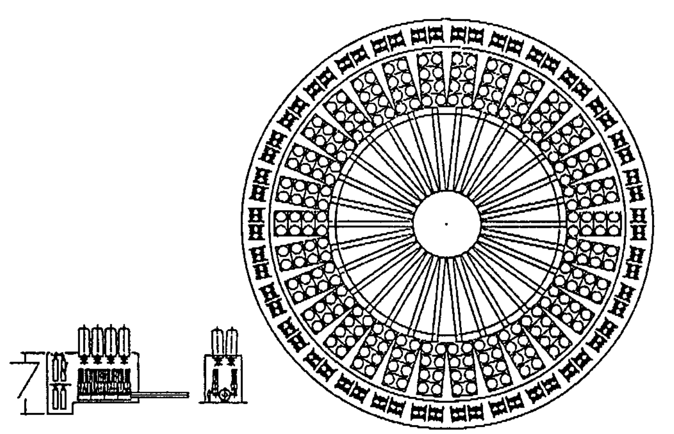

Fig. 1. Conceptual design layout of a thirty module Jupiter Class accelerator.

Figure 1 shows a conceptual design layout of the modular construction of an Inductive Voltage Adder system for a Jupiter Class Accelerator. This system is comprised of 30 modules, each producing an output pulse of 10 MV, 1.8 MA, $\geq$ 100 ns FWHM into a matched resistive load. A module is comprised of four submodules each of which produce a 2.5 MV, 1.8 MA output pulse. The outputs from the submodules are added in series by the Self-Magnetically Insulated Transmission Line (MITL)[3]. A design concept for the components, submodule, and module has been completed and component testing initiated as part of the advanced pulsed power research program at Sandia. Figure 2 is a drawing of the Component Development Testbed. The testbed

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14. ABSTRACT
Jupiter is a proposed 15-20 MJ laboratory x-ray source. It would store ~100 MJ in the Marx generators and deliver~ 500 TW to drive high power z-pinch implosions. The pulsed power requirements for Jupiter were evaluated by a national review panel1 which concluded that the modular IV A technology as used in HERMES III2 is capable of meeting these requirements. Modularity of construction permits design verification with less than a full size system and offers the flexibility to meet changing requirements. A program to validate this approach at the required power levels has begun with the construction and testing of components that will comprise a full scale IV A generator module. The IV A module will provide a nominal 10 MV, 1. 8 MA, 100 ns FWHM output pulse and will consist of four submodules. Each submodule is composed of a Marx generator, two Intermediate Energy Storage Capacitors (ISCs) four Pulse Forming Lines (PFLs), one Voltage Adder Cavity (VAC), plus other associated switches and hardware. A conceptual design for this IV A module has been completed. Initial designs for the ISC, PFL, and their gas switches are also complete and hardware has been procured. Testing of these components is underway at Sandia National Laboratories. Discussions of these designs and results of tests are presented in this paper.

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comprises a Marx generator, one ~30 nF Intermediate Energy Storage Capacitor (ISC), two Pulse Forming Lines (PFLs), and associated gas insulated switches and hardware. The pulse forming components are presently being tested in this facility. The energy available in the Marx limits testing to ~ 2 MV on the PFLs.

II. The Components Development Testbed

The conceptual design for the Jupiter Marx generator calls for $\geq$ 800 kJ stored energy with 56 nominal 3.1 μF capacitors for a total erected capacitance of ~ 56 nF. The component testbed represents one-half of an IVA submodule; therefore, the testbed Marx generator consists of 48 nominal 1.3 μF (27 nF erected capacitance) at about 220 kJ stored energy. This limits the peak operating voltage on the ISC to about 3.5 MV for the testbed configuration as compared to 4.2 MV for the IVA module. An external inductor of about 12 μH is added to the Marx circuit to set the appropriate charge time on the ISC.

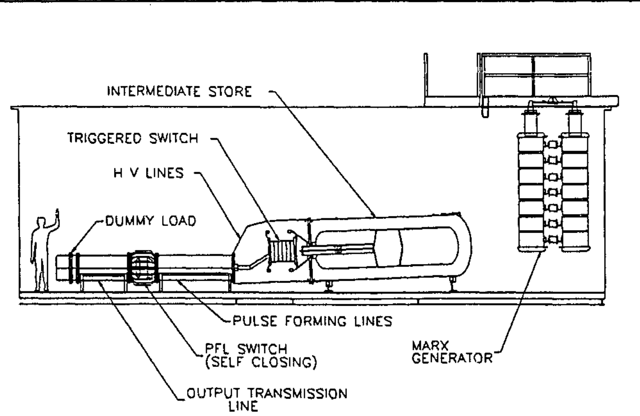

Fig. 2. Drawing of the component development testbed.

The ISC is a single-ended single barrier configuration. It is approximately 14 feet in overall length or about 100 ns of electrical length. The outer conductor is nearly 5 feet in diameter and the impedance is set at ~ 3.4 Ω. Nominal operating voltage for this design is 4.2 MV. Average fields along the outer conductor (+ conductor) are 110 kV/cm with field on the inner conductor at 180 kV/cm.

The ISC has been tested to about the 3.5 MV level while switching the ISC gas switch into a resistive load. There has been one failure of the ISC where the voltage was low enough that the output switch failed to close. The ISC broke down at about 2.5 MV. There was no noticeable damage caused by this breakdown and it was determined by current monitors at each end of the ISC that the breakdown occurred somewhere along the straight coaxial section near the center. This breakdown will be investigated further in the future, but it has had no impact on operations.

The PFLs are designed to operate at ~ 2.5 MV. The ISC to PFL charge is to operate in a "Double Bounce"[4] mode in order to allow for lower voltage operation of PFL charge as well as lower switch voltages (see Figure 3). The PFL output switch is set to close at ~ t_1 where the voltage on the line is about half the peak ringing voltage the line would reach if the switch had not closed. This allows a traveling wave on the PFL and much of the energy is in the magnetic field at switch time so the peak voltage on the switch is much lower. The output voltage is expected to reach about the same level as the switch voltage (V_o) due to the traveling wave. This is unlike conventional matched impedance PFL operation where the output voltage is typically 1/2 V_o.

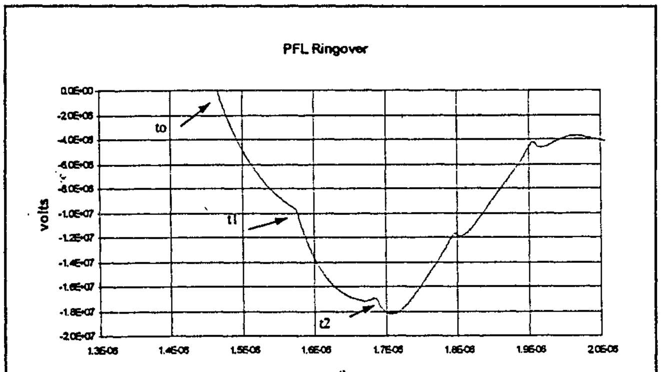

Fig. 3. Simulated PFL charge showing "Double Bounce".

The PFL switches being tested are gas insulated self closing switches (see figure 4). This particular switch is a copy of the cascade section of the HERMES III ISC switch.[5] It consists of ten 1 cm gaps. The field grading is set as uniform as possible across the switch (see figure 5a & 5b). The switch pressure is set so that the switch closes at about 130 ns into the charging waveform for normal operation.

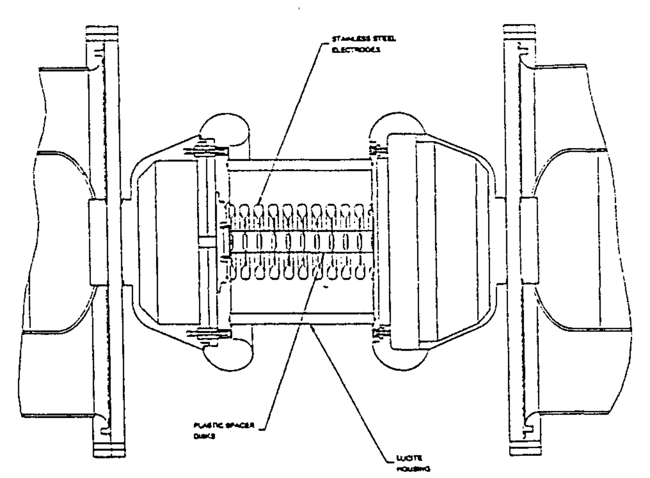

Fig. 4. Drawing of self-closing PFL gas switch.

III. Component Test Results

Initial operation of the PFLs began by using the Output Transmission Lines (OTLs) as resistive loads. The OTLs were filled with low resistivity water and the effective impedance was about 1.5 Ω/line. During these early tests the PFL switches were operated at a pressure of 3 PSIG (~15 PSIA) SF_6. Peak current for this mode of operation is about 350 kA which is very near nominal operating parameters for the Jupiter module. After the first four shots, one of the switches was removed and disassembled for inspection. One section of the cascade switch was found to have only four distinct arc channels indicating that it probably had single channeled on each of the four shots. All other sections showed at least eight arc channels and as many as about fourteen. Our analysis is that the section with only four arc channels was most likely the section that initiated the closure of the switch. The remaining sections were in fact multi-channeling, allowing for low inductance operation.

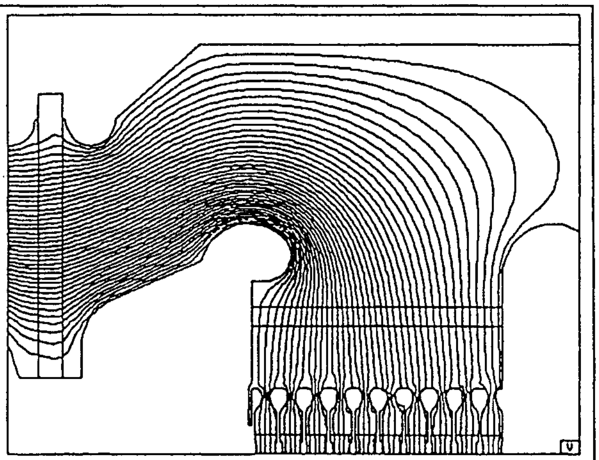

Fig. 5a. Equipotential plot of self-closing PFL gas switch.

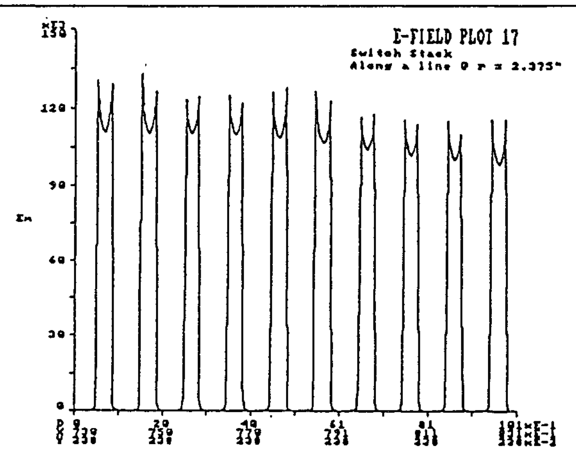

Fig. 5b. Graph of field distribution along cascade electrodes.

Short coaxial resistive load hardware have subsequently been fabricated and installed. PFL switch self-closing voltage versus pressure and PFL-1 to PFL-2 switch timing spread are now being measured using this load hardware. The objective of these PFL switch tests is to establish that switch timing precision in the self-closing (untriggered) mode is sufficiently small for submodule synchronization in the full Jupiter module. During a run of 17 shots, after ~ 70 previous shots characterizing the circuit, the switch voltage versus pressure was scanned from ~ 1.5 to 2.4 MV. The time that voltage was present on the PFL switch varied from ~ 130 ns to ~ 250 ns. The mean scatter time of switch closure (PFL-1 to PFL-2) for this series was -3.9 ns with a 1 σ single switch jitter of 8.8 ns. The minus indicates a bias towards PFL-1 firing first ($0 \pm \sigma$ would indicate nominally simultaneous operations). After this series of shots the switch electrode plates were removed, inspected, and replaced with new electrodes. Appearance of the removed electrodes was consistent with multi-channel operation in the self closing mode and did not show excessive erosion, nor other damage that could lead to short lifetime. In subsequent tests of the new electrodes at a fixed voltage of ~ 2.3 MV the mean of the scatter was 2.2 ns with a 1 σ single switch jitter of 1.5 ns.

This was for a series of nine shots, and indicates that tight time precision can be achieved. A PFL charge voltage discrepancy of ~ 100 kV was noted between PFL-1 and PFL-2 and is being reviewed. It is unlikely that different PFL voltages can occur at the same time given the tight coupling of the single ISC to the PFLs'. This difference can be explained by a calibration error of $\leq$ 5% or a Data Acquisition System (DAS) timing error and reproducible difference in switch breakdown characteristics due to gap assembly tolerance bias.

On shot #148 the input barrier to PFL-2 failed at ~ 2 MV; but, higher voltages had been previously sustained. Disassembly and inspection showed that there was oil and air in the water in the PFL which collected at the barrier triple point. This produced a dielectric discontinuity and field enhancement with a high probability of initiating a breakdown at moderate applied voltage. Multiple features of the breakdown pattern suggests a prior breakdown which could explain the noise level and timing irregularity observed on an earlier shot. This was an ultra high molecular weight polyethylene barrier and was replaced with a Lexan barrier. Approximately 20 subsequent shots at similar voltage levels were run, at which time we experienced another identical failure. Upon disassembly and inspection it was determined that there was a leak in a weld that had allowed oil into the system, as well as the deionized water system introducing air into the PFLs. These deficiencies were corrected and the system operated for approximately 135 additional shots without failure.

The objectives of the present tests are to demonstrate the performance and validate the design of the components of a submodule. The sequence of tests will verify successive stages of energy storage and pulse shaping up to the point of operating a full submodule at the levels required for an IVA pulse power driver. Upon completion of these tests the performance of the hardware for a full module (four each voltage adder cells and associated hardware for a 10 MV system) will have been validated and construction of a full scale IVA module can begin.

IV. Conclusions

The Marx generator will be upgraded to meet design specifications as soon as possible in order to test the ISC at full operating voltage. When complete, data will be generated that will aide in validating large area breakdown concerns. The inductance of the feed from the ISC to the PFL will be reduced to operate in a double bounce mode at the 2.5 MV level. This is to be addressed as time permits.

The PFLs are operating satisfactorily at levels consistent with the conceptual design for Jupiter. Testing of the PFL switches will continue in order to produce a statistically significant database for more reliable prediction of operational stability and life time. Figure 6 shows spreadsheet data of ~120 shots that indicates a 1σ single switch jitter of about 1.2 ns.

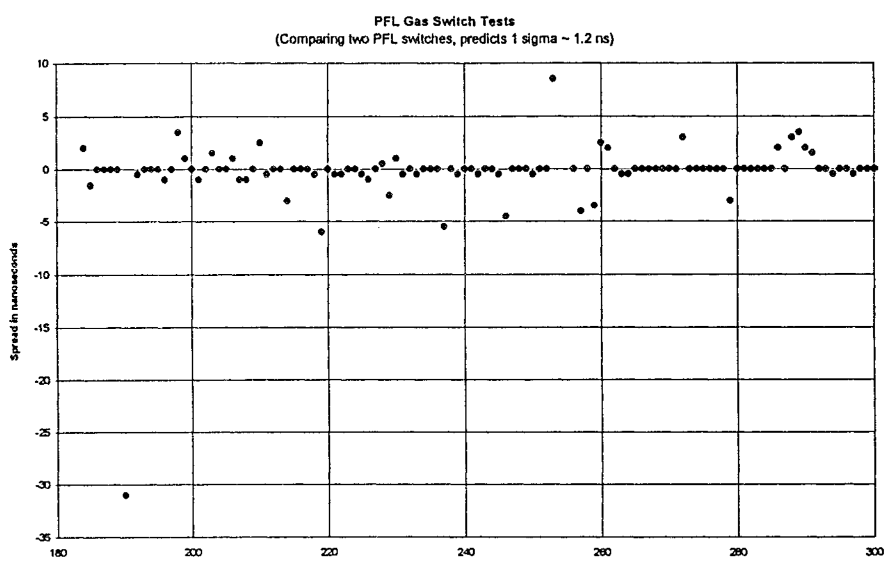

Fig. 6. Spread sheet indicating 1σ single switch jitter of about 1.2 ns.

References

1. Wendland Beezhold, et al., "Jupiter Design Options Study Team" Sandia Report, SAND94-3163·UC-700, printed May 1995.

2. J. J. Ramirez, et al., "HERMES III - A 16 TW Short Pulse, Gamma Ray Simulator", in Proceedings of the 7th International Conference on High Power Particle Beams, Karlsruhe, West Germany, July 4-8, 1988, pp. 143-146.

3. R. C. Pate, et al., "Self-Magnetically Insulated Transmission Line System Design for the 20-Stage HERMES III Accelerator", in Proceedings of the 6th IEEE Pulsed Power Conf., Arlington, VA, June 29-July 1, 1987, pp. 478-481.

4. G. B. Frazier, et al., "Double-Bounce Switching", in Proceedings of the 4th IEEE Pulsed Power Conf., Albuquerque, NM, June 6-8, 1983, pp. 556-558.

5. G. J Denison, et al., "A High-Voltage Multistage Laser-Triggered Gas Switch" in Proceedings of the 6th IEEE Pulsed Power Conf., Arlington, VA, June 29-July 1, 1987, pp. 490-493.